

MILDLY RELATIVISTIC X-RAY TRANSIENT 080109 AND SN 2008D: TOWARDS A CONTINUUM FROM ENERGETIC GRB/XRF TO ORDINARY Ibc SN

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ABSTRACT

We analyze the hitherto available space-based X-ray data as well as ground-based optical data of the X-ray transient 080109/SN 2008D. From the data we suggest that (i) The initial transient ($\lesssim 800$ sec) is attributed to the reverse shock emission of a mildly relativistic ($\Gamma \sim$ a few) outflow stalled by the dense stellar wind. (ii) The subsequent X-ray afterglow ($\lesssim 2 \times 10^4$ sec) can be ascribed to the forward shock emission of the outflow, with a kinetic energy $\sim 10^{46}$ erg, when sweeping up the stellar wind medium. (iii) The late X-ray flattening ($\gtrsim 2 \times 10^4$ sec) is powered by the fastest non-decelerated component of SN 2008D's ejecta. (iv) The local event rate of X-ray transient has a lower limit of $\sim 1.6 \times 10^4 \text{ yr}^{-1} \text{ Gpc}^{-3}$, indicating a vast majority of X-ray transients have a wide opening angle of $\gtrsim 100^\circ$. (v) Transient 080109/SN 2008D indicates a continuum from GRB-SN to under-luminous GRB-/XRF-SN to X-ray transient-SN and to ordinary Ibc SN (if not every Ibc SN has a relativistic jet), as shown in Figure 2 of this *Letter*.

Subject headings: gamma rays: bursts – supernovae: individual: SN 2008D – radiation mechanisms: non-thermal

1. INTRODUCTION

During the past decade, long-duration ($\gtrsim 2$ sec) γ -ray bursts (GRBs), including the subclass of X-ray flashes (XRFs), have been found (1) to be driven by the core-collapse of massive stars (Woosley et al. 19993); thus (2) to be associated with a rare variety ($\sim 1\%$) of type Ibc supernovae (SNe), the so-called hypernovae (HN) (Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003; Malesani et al. 2004; Sollerman et al. 2006; Campana et al. 2006) (but also see Fynbo et al. 2006); and (3) in general to be hosted by the star-forming dwarf galaxies with low metallicity (Fynbo et al. 2003; Fruchter et al. 2006; Stanek et al. 2006). Though the association of GRB/XRF and Ibc SN has been pinned down, what channels make a dying star to produce a GRB or an XRF, and not just a Ibc SN, is still unclear. The progenitor's mass, metallicity, angular momentum, and the configuration and strength of its internal magnetic field play important roles for the generation of GRBs/XRFs and ordinary Ibc SNe.

The serendipitous discovery of the X-ray transient 080109/SN 2008D may shed light on filling in this gap between energetic GRBs/XRFs and ordinary Ibc SNe. We will analyze space- and ground-based data of this transient and SN, focusing on X-ray/radio data because observationally they trace the fastest component of the transient/SN outflow while optical data trace the slower SN ejecta (e.g., Soderberg et al. 2006).

2. SWIFT OBSERVATIONS AND DATA ANALYSIS

During *Swift*/XRT follow-up observations of Ib SN 2007uy beginning at 13:32:49 UT on Jan 9, 2008, an X-ray transient

(Transient hereafter) was identified and reported on Jan 10.58 (Berger & Soderberg 2008a). X-ray emission was already underway at time of trigger. Both Transient 080109 and SN 2007uy are in the same host galaxy, NGC2770, at $z = 0.0065$. The object was within the *Swift*/BAT field of view for approximately 30 minutes prior to the XRT observation but never triggered BAT (Burrows et al. 2008).

Since trigger, the Transient was observed to rise to a maximum flux about 65 seconds, and then subsequently decay until the end of the first orbit, roughly 500 seconds afterwards. We reduced the XRT data in a standard way using the Swift analysis software (HEASoft 6.4) and calibration data. The contamination by a source close to the Transient and pile-up have been corrected.

A general spectral softening was seen during the first orbit. Taking a mean spectrum, the data can be well fitted by either an absorbed power-law $\Gamma = 2.3 \pm 0.2$ and a column density $N_H = 7.6^{+1.4}_{-1.2} \times 10^{21} \text{ cm}^{-2}$ ($\chi^2_{\text{dof}} = 15.1/20$) with respect to the Galactic number $1.7 \times 10^{20} \text{ cm}^{-2}$ or by an absorbed blackbody spectrum with $kT = 0.73 \pm 0.05 \text{ keV}$ in the restframe ($\chi^2_{\text{dof}} = 24.2/20$). For the late X-ray data, the spectral index cannot be well fitted due to the limited photon numbers but $\Gamma \sim 2.1$ is acceptable.

UVOT marginally detected an optical counterpart to the X-ray transient on Jan 9 in the B (3.4σ) and U (3.0σ) filters. After a data gap of 2 days, the source brightened and showed up in both optical and UV. The source then faded until day ~ 3.5 and subsequently brightened again, confirming the onset of SN 2008D (Page et al. 2008).

3. EARLY SPECTROSCOPY AND ITS EVOLUTION

Two spectra were obtained at the ESO VLT equipped with FORS2 starting 07:17 UT on Jan 11. As pointed in Malesani et al. (2008), the overall spectral shape rules out a significant non-thermal afterglow component, but a SN one instead. The presence of broad features reveal SN 2008D's emergence, but the features are not as broad as in the earliest spectra of GRB/XRF-associated SNe such as SN 1998bw and SN 2006aj.

SN 2008D is distinguished for its apparent Ic \rightarrow Ib spectro-

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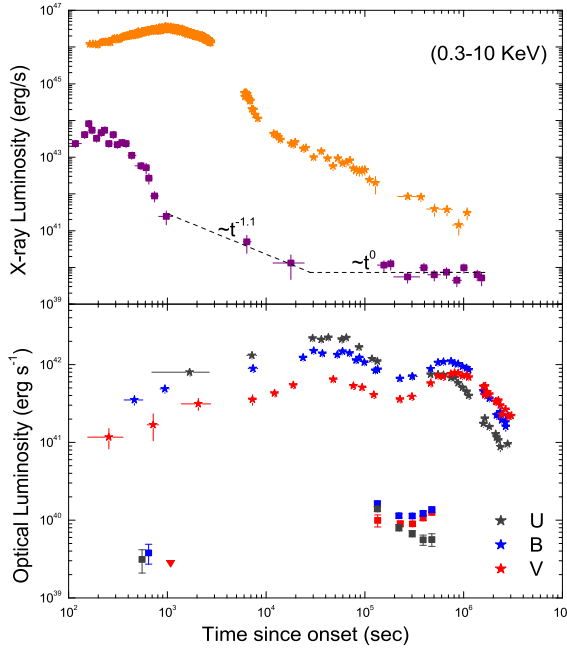


FIG. 1.— Comparison of X-ray transient 080109/SN 2008D (squares) and XRF 060218/SN 2006aj (stars). Data of XRF 060218/SN 2006aj are taken from Campana et al. (2006). *Upper*: Temporal evolution of the X-ray luminosity in 0.3–10 keV. *Lower*: The U (grey), B (blue), and V (red) lightcurves for two events. Data of Transient 080109 have not been corrected for extinction.

scopic evolution. It was classified as peculiar type-Ic on Jan 11, and then as a type-Ic with possibly some He as seen in NIR spectra on Jan 13–15, and later to a type-Ib on Jan 21 (Modjaz et al. 2008 and reference therein). This evolution is reminiscent of SN 2005bf (Folatelli et al. 2006).

4. INTERPRETATION OF THE FOLLOW-UPS

4.1. Real onset time and Spectrum for the first orbit

Though it's impossible to know the exact onset time of the Transient, we may get a rough estimate about this time-back shift. First, non-trigger of BAT approximately 30 minutes prior to the XRT trigger and association with SN 2008D give us confidence that Transient 080109 is a dwarf outburst compared with previous bursts featuring low νF_ν peak energy such as XRF 060218. Second, the existence of a main outburst 30 minutes earlier would make the first orbit lightcurve look like a very sharp flare with a decay index ~ 20 covering three orders of magnitudes in luminosity. Its profile is not similar to the Fast-Rise-Exponential-Decay one typical for GRB/XRF. Considering the above two factors, a back shift of tens to ~ 200 sec is generally acceptable and doesn't affect the temporal decay laws after 1000 sec. In this work, we adopt a back shift of ~ 100 sec.

Should a shock break-out be responsible for the first orbit observation, according to the equation $L = \Omega(\gamma^2 ct)^2 \sigma T_{rest}^4$, where $L \sim 10^{43} \text{ erg s}^{-1}$ is the isotropic luminosity, Ω is the solid angle for the outburst, γ is the Lorentz factor for the outburst with respect to the observer, σ is the Stefan-Boltzmann constant, T_{rest} is the temperature in the restframe, we then have

$$T_{obs} \sim \frac{1.6}{\Omega^{1/4} t^{1/2} \gamma^2} \text{ keV},$$

where T_{obs} is the measured temperature. To match the measured $T = 0.73 \text{ keV}$, a jet-like outflow with $\Omega < 10^{-6}$ is needed, which renders the shock break-out model unacceptable in this event.

4.2. The X-ray transient powered by the reverse shock of the mildly relativistic outflow

The Transient lightcurve is smooth and decays as $t^{-3.7}$. The smoothness largely disfavors that these X-ray photons are powered by internal shocks, and the steep decline rules out that the transient is from the forward shock of an outflow.

We consider a mild-relativistic ($\Gamma_i \sim 3$) outflow with a luminosity $L_m \sim 10^{44} \Omega_o^{-1} \text{ erg s}^{-1}$ decelerated by the stellar wind medium, where Ω_o is the solid angle of the initial transient outflow. The density profile of the stellar wind is $n = 3 \times 10^{35} A_* R^{-2}$, where the free wind parameter $A_* = [\dot{M}/10^{-5} M_\odot \text{ yr}^{-1}][v_w/(10^8 \text{ cm s}^{-1})]$, \dot{M} is the mass loss rate of the progenitor, and v_w is the velocity of the stellar wind (Li & Chevalier 1999). Because of the low luminosity of the outflow while the high density of the stellar wind, the forward-shocked material would move sub-relativistically (i.e., $\Gamma_{fr} \sim 1$) while the reverse shock is mild-relativistic. The reverse shock region is thus very hot and has a very large sideways expansion velocity of $\sim c$, the speed of light. As a result, after the reverse shock crosses the outflow, the shocked outflow will have a large solid angle $\Omega \gg \Omega_o$ if Ω_o is small. So for simplicity we treat the outflow as isotropic.

Now we estimate the synchrotron radiation of the reverse shock at a distance $R_r \sim cT_{90} \sim 10^{13} \text{ cm}$. As usual, we assume ϵ_e and ϵ_B fractions of the shock energy given to the electrons and magnetic field, respectively (Sari et al. 1998). The minimum Lorentz factor of the reverse shock accelerated electrons is $\gamma_{m,r} \sim (\Gamma_i - 1)\epsilon_e(p-2)m_p/[(p-1)m_e] \sim 100$, where $p \sim 2.2$ is the power-law index of the electrons, and the magnetic field generated in the reverse shock region is $B_r \sim [2(\epsilon_B/\epsilon_e)L_m/(R_r^2 c)]^{1/2} \sim 3 \times 10^5 \text{ Gauss}$ (ϵ_B/ϵ_e) $^{1/2} L_{m,44}^{1/2} R_{r,13}^{-1}$. The typical synchrotron radiation frequency $\nu_{m,r} \sim 2.8 \times 10^6 \text{ Hz}$ $\gamma_{m,r}^2 B_r \sim 3 \times 10^{16} \text{ Hz}$, which is in the soft X-ray band and matches the observation. The cooling Lorentz factor is $\gamma_{c,r} \sim 7.7 \times 10^8/(B_r^2 t) \ll \gamma_{m,r}$, so the reverse shock is in the fast cooling phase. At a first glimpse, one might interpret the $\sim t^{-3.7}$ decline as the high latitude emission of the reverse shock. But this requires either a sub-relativistic outflow with a very sharp energy distribution from the outflow center to the outflow side or a $\Gamma_{fr} \geq \text{a few}$. The validity of the former option is hard to estimate. The latter is also difficult to function because $\Gamma_{fr} \approx 1.1 L_{m,44}^{1/4} A_{*, -1}^{-1/4}$. A $\Gamma_{fr} \sim 3$ requires $L_m \sim 10^{47} \text{ erg s}^{-1} A_*$, which is too high to match the observation.

In this work we interpret the steep X-ray decline as the dimmer and dimmer reverse shock emission powered by the weaker and weaker outflow. Within this scenario, the outflow is very likely to be mildly relativistic. If $\Gamma_i \sim \text{tens-hundreds}$, $\gamma_{m,r} \sim 10^3 - 10^4$ and $\nu_{m,r}$ would be $\sim 5 - 500 \text{ keV}$. As a result, the XRT spectrum should be $\propto \nu^{-0.6}$, which is inconsistent with the observed value. A marginally relativistic ($\Gamma_i \sim 1.2$) outflow model is also disfavored because the reverse shock would be very weak. With typical shock parameters, the emission of such a weak reverse shock can not peak at soft X-ray band and is likely to be outshone by the forward shock X-ray emission.

⁶ The convention $Q_x = Q/10^x$ has been adopted in cgs.

4.3. The early X-ray afterglow ($\lesssim 2 \times 10^4$ sec) powered by the forward shock of the Transient outflow

We calculate the synchrotron radiation of the sub-relativistic forward shock when it sweeps up the surrounding stellar wind medium. The minimum Lorentz factor of the shocked electrons, the magnetic field and the cooling Lorentz factor are $\gamma_m \approx 16 C_p \beta^2 \epsilon_{e,-1}$, $B \approx 15$ Gauss $\beta R_{15}^{-1} \epsilon_{B,-1}^{1/2} A_{*, -1}^{1/2}$, and $\gamma_c \approx 34 \beta^{-2} R_{15}^2 \epsilon_{B,-1}^{-1} A_{*, -1}^{-1} t_5^{-1}$, respectively, where $C_p \equiv 6(p-2)/(p-1)$. The maximum specific flux, the typical synchrotron radiation frequency and the cooling frequency (Sari et al. 1998) are respectively given by

$$F_{\nu, \max} \approx 1 \text{ Jy } \beta \epsilon_{B,-1}^{1/2} A_{*, -1}^{3/2} D_{L, 25.9}^{-2}, \quad (1)$$

$$\nu_m \approx 1.1 \times 10^{10} \text{ Hz } \beta^5 C_p^2 R_{15}^{-1} \epsilon_{e,-1}^2 \epsilon_{B,-1}^{1/2} A_{*, -1}^{1/2}, \quad (2)$$

$$\nu_c \approx 4.8 \times 10^{10} \text{ Hz } \beta^{-3} R_{15}^3 \epsilon_{B,-1}^{-3/2} A_{*, -1}^{-3/2} t_5^{-2}, \quad (3)$$

where D_L is the luminosity distance of the source. So the X-ray flux can be estimated as

$$\begin{aligned} F_{\nu_X} &= F_{\nu, \max} \nu_c^{1/2} \nu_m^{(p-1)/2} \nu_X^{-p/2} \\ &= 4.6 \times 10^{-2} \mu\text{Jy } \nu_{X, 17}^{-p/2} \beta^{(5p-6)/2} \epsilon_{e,-1}^{p-1} \epsilon_{B,-1}^{(p-2)/4} \\ &\quad A_{*, -1}^{(p+2)/4} D_{L, 25.9}^{-2} C_p^{p-1} R_{15}^{(4-p)/2} t_5^{-1}. \end{aligned} \quad (4)$$

If $\beta \sim \text{const.}$, i.e., the outflow hasn't been decelerated significantly, we have $R \approx \beta ct$ and $F_{\nu_X} \propto t^{(2-p)/2}$. The decline is thus too shallow to be consistent with the detected $\propto t^{-1.1}$ for the early X-ray afterglow. We then consider an alternative in which the outflow with a energy distribution $E(\geq \beta\Gamma) \propto (\beta\Gamma)^{-k}$ has entered the Sedov regime, thus we have $\beta \propto t^{-\frac{1}{3+k}}$ and $R = \frac{3+k}{2+k} \beta ct \propto t^{\frac{2+k}{3+k}}$. Accordingly, Eqs. (1-3) read $F_{\nu, \max} \propto t^{-\frac{1}{3+k}}$, $\nu_m \propto t^{-\frac{2+k}{3+k}}$, and $\nu_c \propto t$, respectively. The light curves are of

$$F_{\nu} \propto \begin{cases} t^{\frac{4+k}{3(3+k)}} & \text{for } \nu < \nu_m < \nu_c, \\ t^{-\frac{1}{3+k} [1 + \frac{(p-1)(7+k)}{2}]} & \text{for } \nu_m < \nu < \nu_c, \\ t^{-\frac{1}{3+k} [1 + \frac{(p-1)(7+k)}{2}] + \frac{1}{2}} & \text{for } \nu > \max\{\nu_c, \nu_m\}. \end{cases} \quad (5)$$

So the early X-ray afterglow decline $F_{\nu_X} \propto t^{-1.1}$ suggests a very small $k \sim 0.4$ for $p \sim 2.2$, implying that the outflow almost has a very flat energy distribution (i.e., the Transient ejecta is likely expanding with a single bulk Lorentz factor). So we assume $E_{\text{tran}} \approx 4\pi\beta^2 R^3 n m_p c^2$, which yields

$$\beta \sim 0.23 E_{\text{tran}, 46.5}^{1/3} A_{*, -1}^{-1/3} t_4^{-1/3}. \quad (6)$$

Eq.(4) thus reduces to

$$F_{\nu_X} \sim 0.04 \mu\text{Jy } \epsilon_{e,-1}^{1.2} E_{\text{tran}, 46.5}^{1.1} t_4^{-1.2}, \quad (7)$$

which is consistent with the XRT flux $\sim 0.03 \mu\text{Jy}$ at 10^{17} Hz at $t \sim 10^4$ sec (see Fig.1). The outflow energy inferred above is $E_{\text{tran}} \sim 3 \times 10^{46}$ erg, which is larger than the isotropic energy of the X-ray transient by a factor of 10 and is reasonable.

Till here we have shown that a mild-relativistic outflow with an energy $\sim 3 \times 10^{46}$ erg can account for the Transient and the early X-ray afterglow self-consistently, which implies that there was no energetic outburst before the X-ray transient. Should it happen, there would be a bright X-ray afterglow component, which actually could outshine the current data. On the other hand, an earlier outburst would sweep up the stellar wind medium and leave a very low density bubble. The Transient outflow thus cannot get decelerated effectively and cannot account for the following X-ray afterglow data.

4.4. The late X-ray afterglow ($\gtrsim 2 \times 10^4$ sec) powered by the supernova shock

After $\gtrsim 2 \times 10^4$ sec, the X-ray lightcurve gets flattening. We interpret this flattening as the shock emission of the fastest component of the SN ejecta, which moves with a velocity $\sim 0.2 c$ (see Eq. (6) for the limit).

As shown in Eq. (4), if the SN fastest component is energetic enough that hasn't got decelerated significantly in a timescale $\sim 10^6$ sec or even longer, we have

$$F_{\nu_X} \propto t^{(2-p)/2} \sim t^{-0.1},$$

which is consistent with the observed flattening (see Fig.1).

The observed X-ray flux at $\sim 10^{17}$ Hz at $t \sim 10^6$ s is $\sim 0.02 \mu\text{Jy}$, which requires $\beta \approx 0.1^{1/(2p-1)} \epsilon_{e,-1}^{(1-p)/(2p-1)} A_{*, -1}^{-(p+2)/[4(2p-1)]}$. A reasonable choice of $A_* \sim 1$, $\epsilon_{e,-1} \sim 1$, and $\beta \sim 0.2$ leads to that the total energy of the SN fastest component is no less than

$$\begin{aligned} E_{\text{SN}}(\beta \geq 0.2) &\sim 4\pi n R^3 \beta^2 m_p c^2 \\ &\sim 3 \times 10^{48} \text{ erg } A_*^{\frac{5(p-2)}{4(2p-1)}} \epsilon_{e,-1}^{\frac{3(1-p)}{2p-1}} t_6. \end{aligned} \quad (8)$$

For comparison, we plot in Figure 2 the identified energy distribution of the outflows associated with XRT 080109/SN 2008D, together with those of ordinary Ic SNe and the hypernovae associated with energetic GRBs/XRFs. At first glimpse, the main difference between the ordinary Ic SNe and the GRB/XRF-associated ones is the energy of the (mild-)relativistic outflow.

4.5. The radio afterglow: the supernova shock model

Radio emission below the self-absorption frequency, ν_a , would be suppressed significantly. Through the standard treatment (Rybicki & Lightman 1979), for $\nu_a < \nu_m < \nu_c$, we have $\nu_a \approx 3.9 \times 10^{12} \text{ Hz } \beta^{-13/5} t_5^{-1} \epsilon_{e,-1}^{1/5} \epsilon_{B,-1}^{4/5} A_{*, -1}^{4/5}$. While for $\nu_m < \nu_a < \nu_c$, we have

$$\nu_a \approx 2.6 \times 10^{11} \text{ Hz } \beta^{\frac{4p-6}{p+4}} t_5^{-1} \epsilon_{e,-1}^{\frac{2-p}{p+4}} \epsilon_{B,-1}^{\frac{p+2}{2(p+4)}} A_{*, -1}^{\frac{p+6}{2(p+4)}}. \quad (9)$$

The latter seems to be more realistic and considered here. The radio afterglow thus will peak when the observation frequency, ν_{obs} , crosses ν_a at

$$t_{\text{peak}} \sim 3 \times 10^6 \text{ s } \left(\frac{\nu_a}{8.64 \text{ GHz}} \right)^{-1} \beta^{\frac{4p-6}{p+4}} \epsilon_{e,-1}^{\frac{2-p}{p+4}} \epsilon_{B,-1}^{\frac{p+2}{2(p+4)}} A_{*, -1}^{\frac{p+6}{2(p+4)}}. \quad (10)$$

For typical parameters $\epsilon_{e,-1} \sim 1$, $\epsilon_{B,-1} \sim 1$, $\beta \sim 0.1$ and $A_* \sim 1$, we expect the SN radio afterglow will peak at ~ 100 days.

Using Eq. (1) the peak flux can be estimated as

$$F_{\nu_{\text{radio}}, \text{peak}} \sim 1 \text{ Jy}. \quad (11)$$

For $\nu_m < \nu_{\text{radio}} < \nu_a < \nu_c$, $F_{\nu_{\text{radio}}} \propto \beta^2 t^{5/2}$. For $\beta \sim \text{const.}$, we have $F_{\nu_{\text{radio}}} \propto t^{5/2}$, increasing with time rapidly. The current two data reported in GCN (Soderberg et al. 2008; van der Horst et al. 2008) do suggest a quick rise of the radio flux and support our assumption $\beta \sim \text{const.}$ For $\beta \propto t^{-1/(3+k)}$, we have $F_{\nu_{\text{radio}}} \propto t^{5/2-2/(3+k)}$. As long as the observation frequency is above ν_a , the light curve is described by Eq.(5).

5. CONCLUSION AND DISCUSSION

Transient 080109/SN 2008D presents the first evidence for a mild-relativistic outburst, $\sim 10^{46}$ erg, preceding the main SN component, thus confirming previous speculation in SN 2005bf (Folatelli et al. 2006).

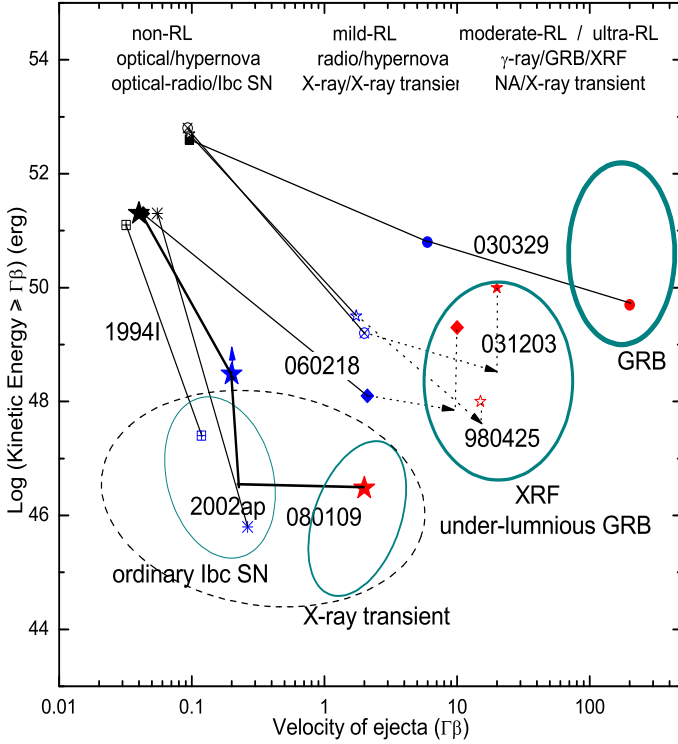


FIG. 2.— Energy distribution for Transient 080109-SN 2008D as well as for GRB-HN, under-luminous GRB-/XRF-HN, and ordinary lbc SNe. RL and NA represent “relativistic” and “not available”, respectively. Part of data from Soderberg et al. (2006) and Kaneko et al. (2006). Sudden drop of the energy distribution in GRB 031203 and XRF 060218 after the prompt emission might be due to the geometry correction and/or a high GRB/XRF efficiency. Transient 080109/SN 2008D marks a transition between populations of ordinary lbc SNe and under-luminous GRB-/XRF-HN. We caution that X-ray transients may account for a majority of lbc SN events.

It sets a lower limit of the local event rate of its kind as $1/3\text{yr}/(0.0276\text{Gpc})^3 \sim 1.6 \times 10^4\text{yr}^{-1}\text{Gpc}^{-3}$, comparable with the local rate of lbc SNe, $\sim 4.8 \times 10^4\text{yr}^{-1}\text{Gpc}^{-3}$, and thus indicates a vast majority of X-ray transients have a wide opening angle of $\gtrsim 100^\circ$. The collimation-corrected energy is of $\sim 5 \times 10^{45}$ erg. The wide angle budget, together with the self-consistent interpretation of the transient and its early afterglow with the on-beam model, largely rules out the off-axis viewing model for this transient.

The host NGC2770, a spiral galaxy with copious $\text{H}\alpha$ sign, stands out from the star-forming dwarf galaxies typically hosting GRBs/XRFs. Transient 080109 puts itself on the upper border of the nearby GRB/XRF collection in terms of the host metallicity (Berger & Soderberg 2008b; Sollerman et al. 2005).

As a result, this event may unveil a continuum from energetic GRB (top-right of Figure 2) to ordinary lbc SN (bottom-left of Figure 2).

(1) Whether or not every lbc SN has a quasi-jet outburst preceding the main SN component is still uncertain even the discovery of Transient 080109. For this reason we mark the ordinary lbc SN and X-ray transient/SN populations with a dash ellipse in Figure 2.

(2) Soderberg et al. (2006) showed that producing GRBs/XRFs needs a relativistic ejecta carrying at least 10^{48} erg. We show in this Letter that X-ray transient population couples $\sim 10^{46}$ erg to relativistic material regarding this found one marks the transition between GRB/XRF and ordinary lbc.

(3) While under-luminous GRBs/XRFs are likely powered by moderate-relativistic material, X-ray transients are likely powered by mild-relativistic material.

(4) GRBs have an average opening angle of $\sim 10^\circ$ while a vast majority (if not all) of X-ray transients have a much wider one of $\sim 100^\circ$. There is a negative correlation between radiated energy and opening angle from GRB to XRF to X-ray transient.

(5) Materials with higher bulk Lorentz factor tend to have a shallower energy-velocity distribution leading to spikeful behavior as shown in GRB/XRF prompt lightcurves and hypernova’s broad-lined spectra. Materials with lower bulk Lorentz factor tend to have a steeper energy-velocity distribution and thus largely couple with each other leading to spikeless/little-spiked behavior as shown in various optical afterglows. The decay laws in terms of velocity for each event in Figure 2 (from left to right) matches this principle.

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